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High resolution study of (e, e′p) reactions

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Abstract : The nuclear structure information that can be obtained from (d, ^{3}He) and (e, e′p) reactions is outlined The spectroscopic factors and the occupation numbers extracted from recent high-resolution studies of the (e, e′p) reactions are reviewed The importance of the information on root-mean-square radii of proton orbitals for $12 \leq A \leq 208$ is discussed

Keywords : Nuclear structure, nuclear reaction

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1. Introduction

During the last forty years, studies on the stripping and pickup reactions using light projectiles have yielded detailed information on the excitation energy, spin-parity and spectroscopic factors for the nuclear levels. These nuclear structure studies have provided strong evidence for the validity of the nuclear shell model.

Because of the strong absorption effects in the case of one-nucleon transfer reactions, such as the (d, ^{3}He), only the tail part of the picked-up nucleon wavefunction contributes to the reaction cross-section ; thus the spectroscopic factors extracted are very sensitive to the nuclear potential used to describe the bound-state wave function of the nucleon [1]. This uncertainity is largely removed in the case of the proton-knockout reaction such the (e, e′p) induced by high energy electrons because the reaction cross section is sensitive to the bound proton wave function inside the nucleus also.

Earlier work till 1984 [2], had indicated the importance of the (e, e′p) reaction in deducing the wave function of the knocked-out proton. During the last 10 years, availability of high resolution spectrometers nas made it possible to make a detailed study of the excited states of nuclei. One such facility at NIKHEF, Amsterdam [3], has provided a beam of 500-MeV electrons with a detection system having an energy resolution of about 200 keV.

The plane-wave Born approximation describing a direct one-step process for the A(d, ^{3}He)B and the A(e, e′p) B reactions are shown schematically in Figure 1. The (e, e′p)

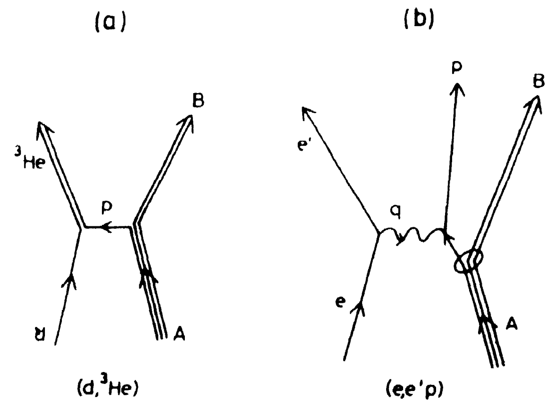

Figure 1. Schematic representation of the direct one-step process for (a) the (d, ^{3}He) reaction and (b) the (e, e′p) reaction.

reaction is described as a one photon-exchange Feynman diagram. In the relativistic formalism, the cross section is described in terms of a spectral function containing an integral over the bound-state proton wave function [4].

2. The RMS radii of single nucleon orbitals

For the case of nucleons moving independently in a harmonic oscillator potential, the expectation value of the potential energy is given by the virial theorem as

$$< 1/2\, mw^2 r^2 > \; = \; 1/2\, E_t,$$

where E_t is the total kinetic energy of the nucleons *i.e.*,

$$E_t = \sum \hbar w(N + 3/2),$$

where $N = 2(n-1) + l$, n is the radial quantum number and l is the orbital quantum number of the nucleon.

Hence the root-mean-square (RMS) radius R_N for the valance nucleon is given by

$$R_N^2 = \; < r^2 > \; = b^2\,(N + 3/2),$$

where $\qquad b^2 = \hbar / mw$ and $\hbar w = 40 / A^{1/3}$.

Also $< r^2 >$ is defined by

$$< r^2 > \; = \int R_{nl}^2(r)\, r^4\, dr,$$

where R_n is the radial wave function of the bound nucleon. Thus

$$R_N = K\left[(N + 3/2)\, A^{1/3}\right]^{1/2}, \qquad \text{where } K \text{ is a constant.}$$

Using the data available on RMS radii [5], a plot of R_N Vs $[NA^{1/3}]^{1/2}$ would give a straight line with a slope of 1.24 + 0.08 (3–N) for $2 \leq N \leq 4$. The (e, e′p) reactions have provided RMS radii for a large number of nuclei with $12 \leq A \leq 208$.

3. Study of the (e, e′p) reactions

In the experiments on (e, e′p) reactions, the scattered electron and the knocked-out proton are detected in coincidence using two high resolution spectrometers [3, 4]. The experimental momentum distribution for the transition to each state in the residual nucleus is measured and compared with DWIA calculations. Both spectroscopic factors and RMS radii are deduced from these fits.

In the case of ^{51}V target, proton pickup or knockout leads to the 0^+, 2^+, 4^+ and 6^+ states in ^{50}Ti corresponding to the coupling of the two remaining $1f_{7/2}$ protons. The information deduced for these four states from (e, e′p) reaction [4] and (d, ^3He) reaction [6] is summerised in Table 1. It is also experimentally determined that the occupation

Table 1. Spectroscopic factors (S) and RMS radii for the $1f_{7/2}$ multiplet in ^{50}Ti.

Level J	Ex (MeV)	(e, e′p)^a RMS radius (fm)	(e, e′p)^a S	(d, ^3He)^b S	Theory^c S
0^+	0 0	4.21	0 365	0 30	0.75
2^+	1 55	4 19	0 155	0 13	0 34
4^+	2.68	4.20	0.328	0.27	0.64
6^+	3.20	4.22	0.485	0.41	0.95

(a) Ref 4, (b) Ref 6, (c) For pure $(1f_{7/2})^n$ configuration [4]

probability for the $1f_{7/2}$ proton orbital in ^{51}V is 57% as compared to the single-particle shell model value of 3/8 or 37.5%. The occupation probability for the deeper orbitals such as the $1d_{5/2}$ is about 78% instead of 100%.

Detailed (e, e′p) studies on ^{12}C [7], ^{28}Si, ^{31}P, ^{32}S [8], ^{40}Ca [9, 10], ^{48}Ca [10], ^{51}V [4], ^{90}Zr [4], ^{205}Tl [12], and ^{206}pb and ^{208}pb [11] have thrown light on the structure of nuclei with $12 \leq A \leq 208$.

4. Conclusions

During the last 15 years, high-resolution studies of the (e, e′p) reaction on nuclei with $12 \leq A \leq 208$ have given detailed information on the nuclear structure. A very recent review [13] summarises the present status of the subject. Studies on (e, e′d) and (e, e′α) are expected to be carried out in the near future at NIKHEF, Netherlands and CEBAF, USA.

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